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**Mechanism of Lubrication for Solid Carbon Materials
in Vacuum to 10^{-9} Millimeter of Mercury**

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The friction and wear characteristics of various carbon materials sliding on metals and aluminum oxide were determined in vacuum at ambient pressures from 760 to 10^{-9} mm Hg. The friction and wear experiments were conducted with a hemispherically tipped carbon rider, under a load of 1000 gm, sliding on various disks rotating at a speed of 390 ft per minute. The results of this investigation show that additional research on carbon in vacuum is warranted. Adsorbed surface films present on both carbons and metal, as well as the presence of oxide on metals, appreciably influenced the friction and wear obtained with carbons in vacuum. Some impregnants were beneficial in reducing friction and wear of carbon in vacuum while others were not.

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Introduction

MECHANICAL devices that must operate in the vacuum of outer space for extended time periods require lubricating materials that are resistant to evaporation. In more conventional lubrication practice, mechanical carbons (carbons having high mechanical strength) have been successfully used as self-lubricating bearing and seal materials in a wide variety of applications. These carbons do not evaporate in vacuum at temperatures of interest. The potential usefulness of carbon-graphite materials for lubrication in vacuum is, however, questionable. The question is based on the adsorbed film theory of lubrication by graphite, which is widely discussed in the literature (1-7). Thus, in the extreme vacuum of space it might be anticipated that desorption of moisture or gases from the surfaces of the carbon-graphite particles would occur and, therefore, its lubricating ability would be lost. Such expectation is supported by experience (during World War II) with brushes for aircraft generators that wore ("dusted") rapidly during high-altitude flight (8).

The solution of the high-altitude brush problem involves the use of certain additional agents or adjuncts as impregnants in the pores of the carbon bodies (8). In considering the possible use of carbons in space applications, an approach to the problem might be to explore the use of similar adjuncts.

Further data (9) suggest that adsorbed moisture or gas films on lamellae are not the exclusive factor that provides lubricating ability for graphite. Rather, it was indicated that the failure of graphite to lubricate under certain conditions (such as high temperature) was due to the lack of proper adherence to surfaces being

lubricated. The same factors are important whether graphite is used as discrete particles or supplied from the structure of a solid body. In the investigation of Reference (9) it was demonstrated that surface conditions, such as oxidation, contributed to effective lubrication by graphite in the absence of moisture. Either oxidized metal films on mating surfaces or the use of soft metal oxides with the graphite gave surface adherence that was conducive to effective lubrication. Further, one of the possible mechanisms by which the high-altitude adjuncts may function is as a bonding agent in helping to provide an adherent film on metal surfaces.

The vacuum of outer space (e.g., 10^{-9} - 10^{-13} mm Hg (torr)) is at a pressure that is many orders of magnitude lower than the altitude level (at 35,000 ft the pressure is 179 mm Hg) at which the generator brush problem was noted. The understanding of fundamental lubrication processes with graphite material would be enhanced by study at pressures associated with space. Also, if mechanical carbon has a lubricating capability in extreme vacuum (or if such capability can be developed), it might be a very useful material (because of its low vapor pressure) in devices that must operate in space.

The objective of this investigation was to obtain a better understanding of the mechanisms of graphite lubrication mentioned above with respect to space lubrication problems. In order to accomplish this objective, the influence on friction and wear of the following was determined in vacuum (10^{-9} mm Hg): (a) varied graphitic carbon content in mechanical carbons, (b) various metals as the mating surface for typical mechanical carbons, (c) varied impregnations in mechanical carbons, and (d) varied ambient pressure (vacuum) conditions for typical mechanical carbons.

Friction and wear experiments were conducted with $\frac{3}{16}$ -inch radius rider specimens of various carbons in sliding contact with the flat surfaces of $2\frac{1}{2}$ -inch diameter rotating disks of several metals. Pressures during the experiment were varied from 10^{-9} mm Hg to atmospheric

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pressure. Evaporation studies of impregnants were run at 10^{-6} – 10^{-7} mm Hg and temperatures to 1000 F.

Apparatus

The apparatus used in this investigation is described in detail in Reference (10) and is shown in Fig. 1. The

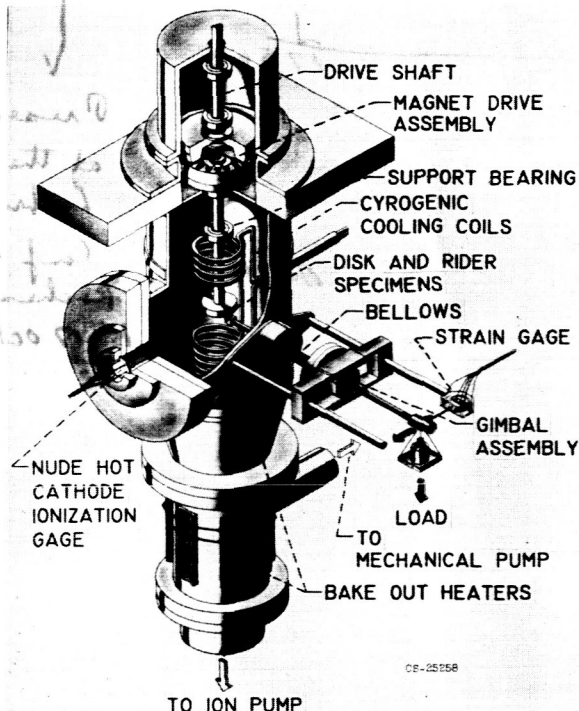


FIG. 1. Test apparatus

basic elements of the apparatus were the specimens (a $2\frac{1}{2}$ -inch diameter flat disk and a $\frac{3}{16}$ -inch radius rider specimen) mounted in a vacuum chamber. The disk specimen was driven by a hydraulic motor and a magnetic-drive coupling. The coupling was composed of two 20-pole magnets separated by a distance of 0.150 inch with a 0.030-inch diaphragm between magnet faces. One magnet was the driver magnet and was outside the vacuum system. It was coupled to a hydraulic motor. The second magnet was enclosed in a nickel alloy housing (cut-away in Fig. 1) and was mounted on one end of the shaft within the chamber. The end of the shaft opposite the magnet contained the disk specimen.

The rider specimen was supported in the specimen chamber by an arm that was gimbal- and bellows-mounted to the chamber. A linkage at the end of the retaining arm away from the rider specimen was connected to a strain-gage assembly. The assembly was used to measure frictional force. Load was applied through a dead-weight loading system.

Attached to the lower end of the specimen chamber was a 400-liter-per-second ionization pump and a mechanical forepump using liquid-nitrogen cold traps. The pressure in the chamber was measured adjacent to the specimen with a nude hot cathode ionization gage.

In the same plane with the specimens and ionization gage was a diatron-type mass spectrometer for measuring gases present in the vacuum system. A 20-foot long $\frac{3}{16}$ -inch diameter stainless steel coil was used for cryo-pumping of the vacuum system with liquid nitrogen and liquid helium.

Specimen cleaning procedure

The metal disks used in friction and wear experiments were finish ground to 4–8 μ inches. Before each experiment, the disks were given the same preparatory treatment. This treatment consisted of (a) a thorough rinsing with acetone to remove oil and grease, (b) polishing with moist levigated alumina on a soft cloth, and (c) a thorough rinsing with tap water followed by distilled water. For each experiment, a new set of specimens was used.

Results and discussion

FRICTION AND WEAR OF 100-PER CENT ELECTROGRAPHITIZED CARBON SLIDING ON VARIOUS METALS

It has been demonstrated in many problem areas that the metal surfaces against which carbon materials run can exert a considerable influence on the friction and wear. It was decided, therefore, to explore the role of varied mating metals for 100% electrographitized carbon sliding in vacuum (10^{-7} mm Hg). The results obtained in these experiments can be seen in Fig. 2. The lowest

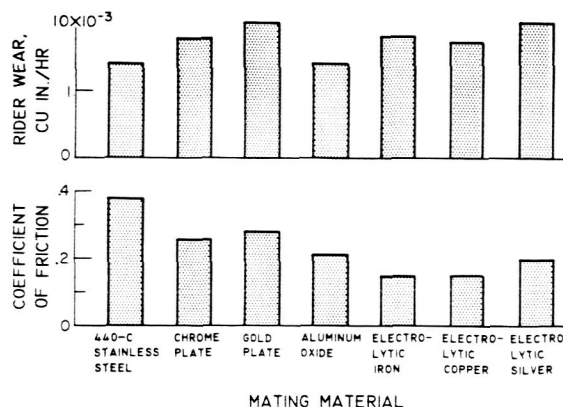


FIG. 2. Effect of mating materials on coefficient of friction and rider wear for 100% electrographitized carbon in vacuum (10^{-7} mm Hg). Sliding velocity, 390 feet per minute; load, 1000 gm; duration of run, 1 hour.

coefficients of friction were obtained for the carbon sliding on electrolytic iron and electrolytic copper. The best wear results, however, were obtained with 100% electrographitized carbon sliding on 440-C stainless steel. The greatest wear to carbon surfaces was obtained with gold plate and electrolytic silver as mating surfaces. This is significant because it was with these two metals that no visual evidence of a transferred carbon film to the metal surface was obtained. All the other metal surfaces

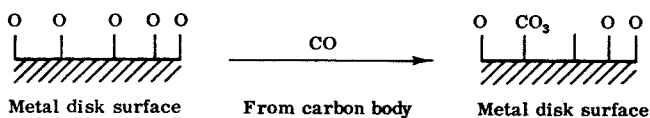
are "oxide formers," and, with all of them, carbon transfer films were present. Such transfer films have been shown to be essential for effective lubrication by graphite materials (9). Although these experiments were conducted in vacuum, residual metal oxides present on the surface have low enough evaporation rates to be retained on the metal surface at an ambient pressure of 10^{-7} mm Hg (and room temperature).

MECHANISM OF ADSORPTION OF CARBON TO METAL

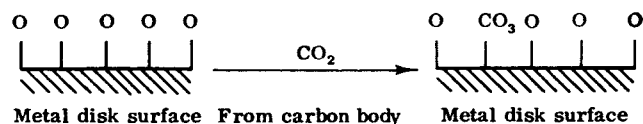
There exist two possible types of bonding of carbon to the metal: first, direct bonding with the formation of metal carbides (11), and second, the chemisorption of carbon and carbon oxides to the metal oxides. The formation of metal carbides would require intimate contact of carbon and metal. This is not possible at ordinary temperatures and pressures because metal and carbon oxides are present on both surfaces and the oxides are thermodynamically more stable than the carbides. The chemisorption of carbon and carbon oxides to metal oxides is more likely than direct bonding (12). Chemisorption will proceed without extremely high temperatures or pressures. In addition, numerous references in the literature indicate the presence of adsorbed films on both carbons and metals (13-21).

The chemisorption of carbon (C) to the metal oxide (O-M) may be achieved with the formation of a complex with carbon being bonded to a metal oxide ($-C-C-O-M$). If the bonds between carbon and oxygen and between carbon and the metal are resonating double or triple bonds similar to those in the carbonyls, the bond energy binding the carbon to the surface is considerably higher. This type of attachment may occur for nascent surfaces generated in the process of sliding.

When oxygen is chemisorbed on the carbon surface, as is generally the case, the adsorption may occur by the mechanism considered in References (16) and (21). The adsorption of a carbon monoxide type structure (resulting from the chemisorption of a single oxygen atom on carbon within the carbon surface) on an oxygenated surface (metal oxide) may occur in the following manner:



The adsorption of a carbon dioxide-type structure (resulting from the chemisorption of two oxygen atoms on a carbon atom within the carbon surface) on an oxygenated surface (metal oxide) may occur in the following manner:



The chemisorption of a carbon monoxide-type structure results in the formation of a carbonate with a new site

on the metal surface exposed for further reaction of the metal with oxygen or other gases. The chemisorption of a carbon dioxide type of structure also involves the formation of a carbonate on the metal surface; with the adsorption of a carbon dioxide type of structure, however, no additional sites on the metal surface are exposed for reaction or adsorption.

Adsorption of the carbon monoxide type structure from the carbon body may occur on metal oxides in a reversible manner. With this reversible type adsorption, the carbon monoxide type structure can be desorbed. Often, however, depending upon the surface to which the carbon monoxide is adsorbed, desorption only occurs by the removal of oxygen from the metal oxide, that is, by the desorption of carbon dioxide. The latter type of reaction is irreversible and can leave a nascent metal surface.

The removal of these chemisorbed structures from metals like copper, nickel, cobalt, iron, and chromium can involve energy levels of 20-100 kcal per mole (22). The wide range of adsorption energies results from the type of bond, which depends on the nature of both the metal and the adsorbing species. Once all the active oxygen sites on the metal surface have been occupied by carbon atoms or carbon complexes, a carbon film can be established on the metal surface, and the sliding process can become one of carbon sliding on carbon rather than carbon on metal.

EFFECT OF GRAPHITE CONTENT ON THE FRICTION AND WEAR OF CARBON

The adsorbed films on the carbon surfaces are also known to affect very markedly the friction and wear characteristics observed for these materials at reduced ambient pressures. In order to determine the extent of this effect, some friction and wear experiments were

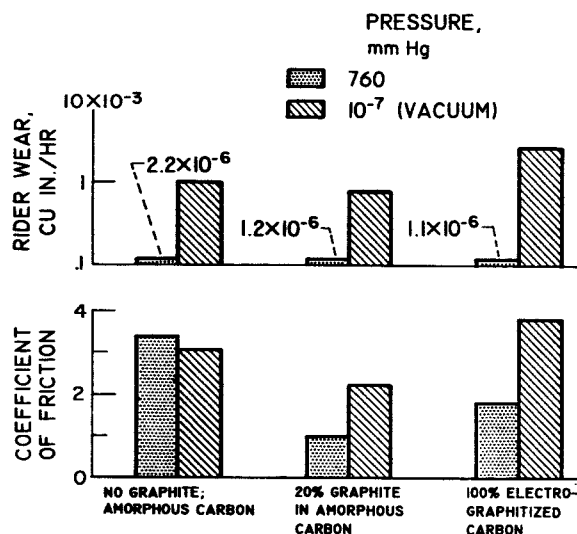


FIG. 3. Effect of graphite content on coefficient of friction and rider wear for carbon compositions sliding on 440-C stainless steel in air and vacuum. Sliding velocity, 390 feet per minute; load, 1000 gm; duration of run, 1 hour.

conducted with three carbon compositions at two pressures, 760 and 10^{-7} mm Hg. The carbons were an amorphous carbon, a 20% graphite carbon (commonly used in mechanical seals), and a fully electrographitized carbon. The results obtained in these experiments are presented in Figs. 3 and 4. With all three carbon compositions, an increase in wear of nearly three orders of magnitude occurred in vacuum. These results indicate the magnitude of friction and wear in vacuum in the absence of the protective surface films (water, oxygen, hydrocarbons, and sulfur). For comparative purposes, photomicrographs of the rider wear scar on the 100% electrographitized carbon rider run at 760 and 10^{-7} mm Hg are presented in Fig. 4.

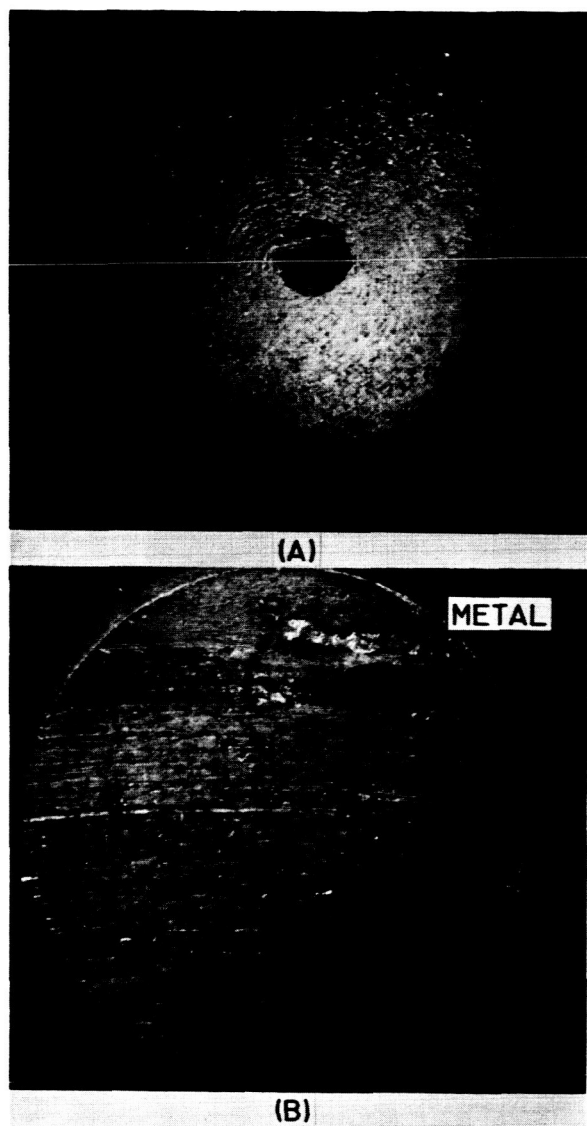


FIG. 4. Photomicrographs of wear areas on 100% electrographitized carbon rider specimens run in air and vacuum. The disk specimen was 440-C stainless steel. The sliding velocity, 390 feet per minute; load, 1000 gm; duration of run, 1 hour. $\times 20$. (a) 760 mm Hg; (b) 10^{-7} mm Hg.

Since, from Fig. 3, the graphite in a carbon appears to have an influence on the friction coefficient and wear obtained in vacuum, more definitive experiments were conducted at 10^{-7} mm Hg. The results obtained in these experiments are presented in Fig. 5, where the friction

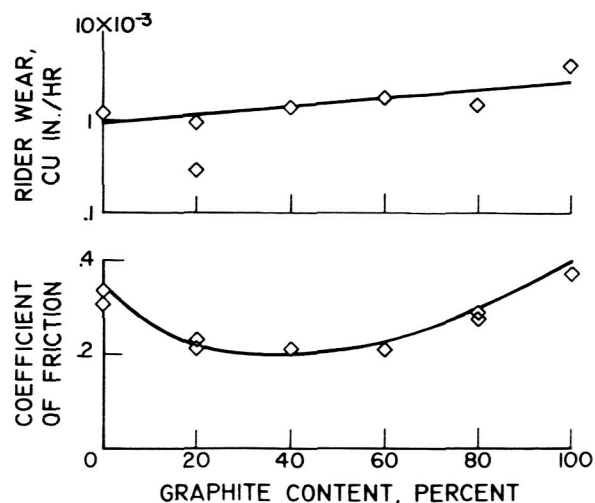


FIG. 5. Effect of graphite content on coefficient of friction and rider wear of various carbon compositions sliding on 440-C stainless steel. Sliding velocity, 390 feet per minute; load, 1000 gm; ambient pressure, 10^{-7} mm Hg.

coefficient and rider wear are plotted against graphite content. The 20, 40, and 60%-graphite samples gave the lowest friction coefficients in vacuum. The wear was lower at lower graphite contents. These results very closely parallel the results obtained in the study of Reference (23) at approximately 760 mm Hg. The stated graphite contents are accurate within 10% and were established according to the manufacturer's advice that was confirmed by X-ray diffraction and other techniques described in Reference (23).

THE INFLUENCE OF BAKEOUT AND AMBIENT PRESSURE ON THE FRICTION AND WEAR OF CARBON

Since the adsorbed gases are chemisorbed as well as physically adsorbed to surfaces, not only vacuum but high temperatures are required to remove the adsorbed gases on carbon surfaces. It is extremely difficult to remove oxygen from carbon completely because of the strong bond of chemisorption formed between them. Temperatures in excess of 3800 F in vacuum are required to remove the oxygen completely; even then, it is only released as carbon monoxide (24). The friction and wear characteristics of 20% graphite carbon were determined at 10^{-7} and 10^{-9} mm Hg with a bakeout to remove gases; the results obtained are presented in Fig. 6. When the ambient pressure was reduced from 10^{-7} to 10^{-9} mm Hg, an increase in friction was observed.

The pressure of 10^{-9} mm Hg was obtained with liquid-helium cryopumping, which reduces the residual oxygen concentration in the system appreciably. When

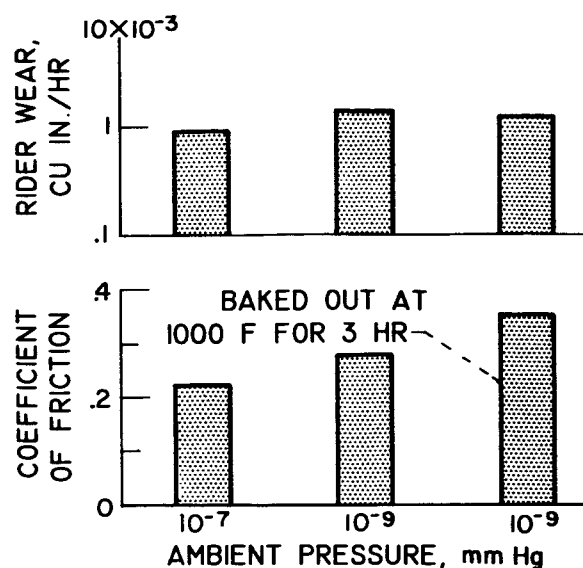


FIG. 6. Effect of ambient pressure and bakeout on coefficient of friction and rider wear for 20% electrographitized carbon sliding on 440-C stainless steel in vacuum. Sliding velocity, 390 feet per minute; load, 1000 gm; duration of run, 1 hour.

the carbon specimens were heated to 1000 F in vacuum for 3 hours prior to the experiment and the pores were backfilled with argon, the coefficient of friction increased again to 0.35. A similar result was obtained by using a 2000 F specimen bakeout.

Friction experiments were conducted at various pressures in an attempt to determine the effect of various ambient pressures on the coefficient of friction for carbon sliding on stainless steel (440-C). Experiments with the same specimens were run at various pressure limits, that is, the apparatus was brought to a specified pressure and held until equilibrium was reached, and then the friction experiment was started. The experiment was run at various pressures from 760 to 10⁻⁹ mm Hg. The results obtained in these experiments are presented in Fig. 7a. When the experiment was started at 10⁻⁹ mm Hg and the pressure gradually increased, the friction coefficient generally decreased. When the pressure was raised above 10⁻¹ mm Hg, the friction coefficient dropped to a value of about 0.08. As the pressure was further increased toward atmospheric (760 mm Hg), the friction coefficient again began to increase and at atmospheric pressure reached a value of about 0.3. When the experiment was started at atmospheric pressure and the pressure decreased, the friction coefficient again decreased to a minimum at about 10⁻¹ mm Hg. The friction coefficient increased gradually and, at 10⁻⁵ mm Hg, reached the value achieved in experiments started at 10⁻⁷ mm Hg. The friction curve obtained in the experiment started at atmospheric pressure did not retrace those obtained with the experiments started at 10⁻⁷ mm Hg. The difference in friction coefficients at pressures between 10⁰ and 10⁻⁵ mm Hg may be attributed to adsorbed surface films. The low friction values obtained

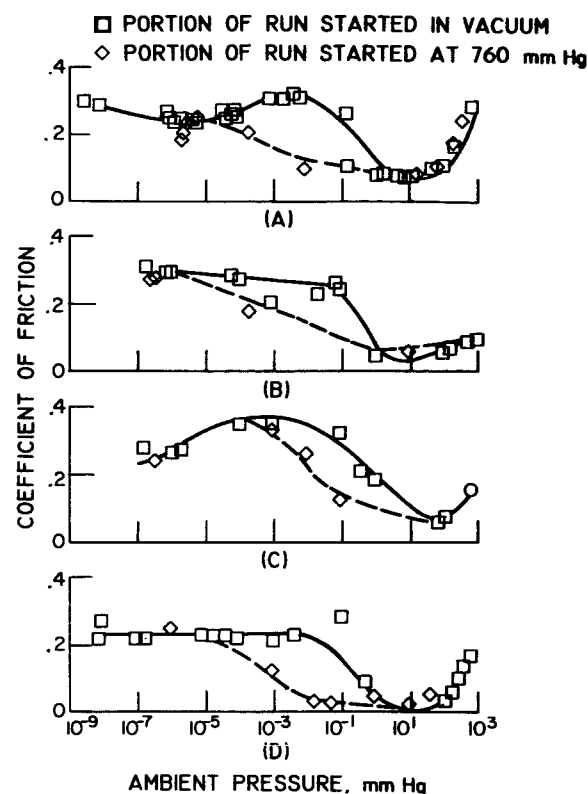


FIG. 7. Effect of disk material on coefficient of friction for 20% graphite carbon at various ambient pressures. Sliding velocity, 390 feet per minute; load, 1000 gm; temperature, 75 F. (a) Disk material, 440-C stainless steel; (b) disk material, chrome plate; (c) disk material, electrolytic copper; (d) disk material, aluminum oxide.

between 10⁻¹ and 100 mm Hg were of some concern, and wear experiments were, therefore, conducted at 760, 5, and 10⁻⁷ mm Hg. The values shown in Table 1

TABLE 1
Friction and Wear of 20 Per cent Graphite Carbon
Sliding on 440-C Stainless Steel

	Pressure (mm Hg)		
	760	5	10 ⁻⁹
Coef. of frict.	0.30	0.06	0.28-0.31
Rider wear (cu in./hr)	1.2 × 10 ⁻⁶	4.2 × 10 ⁻⁸	9.2 × 10 ⁻²

were obtained. The lowest wear and friction values were obtained at 5 mm Hg. The difference in friction coefficient obtained in Figs. 7a and 3 at atmospheric pressure with 20% graphite carbon may result from the fact that the carbon used in Fig. 7a had been degassed in vacuum at 1000 F prior to use.

Friction experiments at various pressures were conducted with this same carbon composition on mating surfaces other than stainless steel, and the results obtained with chromium plate, electrolytic copper, and aluminum oxide are presented in Figs. 7b, c, and d. In each set of experiments minimum friction was obtained at about 10 mm Hg, which indicates that the mating sur-

face did not appreciably influence the results at that pressure. In order to resolve the cause of this effect, a friction experiment was conducted at various ambient pressures using nitrogen gas bleed to provide a nitrogen atmosphere in the chamber. The results obtained in this experiment are presented in Fig. 8. The carbon had been

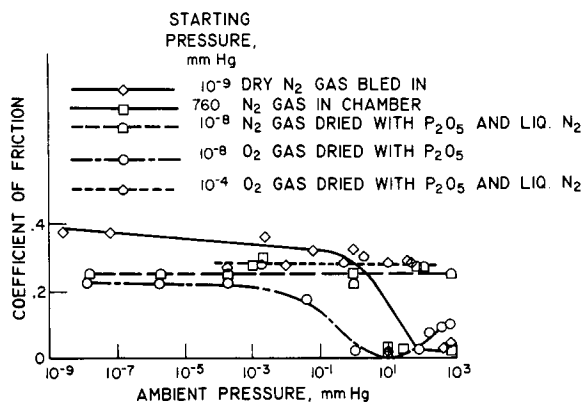


FIG. 8. Effect of bleeding in various gases on coefficient of friction of 20% graphite carbon sliding on 440-C stainless steel at various ambient pressures. Sliding velocity, 390 feet per minute; load, 1000 gm; temperature, 75 F.

baked out in vacuum at 2000 F for 3 hours prior to the experiment. The coefficient of friction was initially about 0.38 and gradually decreased with increasing pressure. At 1 mm Hg the friction dropped to approximately 0.02 and remained low to 760 mm Hg.

The same experiment was then repeated with pure oxygen to determine the effect of one of the other principal constituents of air. The results obtained in these experiments are also presented in Fig. 8. Since it has been demonstrated in the literature (15) that even gases dried by perchlorate contained sufficient moisture (10^{-4} mg water per liter gas) to contaminate carbon surfaces with adsorbed moisture, both oxygen and nitrogen were carefully dried with phosphorous pentoxide. With phosphorous pentoxide, however, the water concentration is reduced to only 2.0×10^{-5} mg per liter of gas; this water concentration in a system amounts to about 3×10^{11} molecules of water per cubic centimeter (16). The gas was therefore dried with phosphorous pentoxide and two liquid-nitrogen cold traps connected in series. After this drying the gases were considered to contain less than 1.0×10^{-23} mg per liter of water vapor (24). The results obtained with ultradry nitrogen and oxygen are presented in Fig. 8; no decrease in friction was observed over the pressure range where a decrease in friction was previously obtained with the conventionally dried gases. These results indicate that the decrease in friction coefficient observed in Fig. 7 at about 10 mm Hg was a moisture effect. The water vapor was adsorbed on the surface and desorbed at a pressure of approximately 10 mm Hg.

Unlike other surfaces, carbon can undergo sorption of three types: (a) physical, (b) chemical, and (c) persorp-

tion, which is a type characteristic of adsorption agents such as carbons and silica gel (24). Persorption involves the capillary condensation of gases or liquids within the structure of the adsorbent (e.g., in a porous carbon). The adsorption of water vapor on carbon is quite well known. Examination of the literature indicates a number of references which show that the adsorption of water occurs on carbon both physically and chemically (15-18, 25, 27). The physically adsorbed water is very readily removed in vacuum. Removal of the chemically adsorbed water involves a dissociation of water on the carbon surface into hydrogen and hydroxyl groups, which are then chemisorbed to the carbon surface. This process is a reversible one, and the groups are recombined on desorption to form water (15, 28). It is believed that the minimum values of the friction curves obtained in Fig. 7 between 1 and 10 mm Hg are due to the physically adsorbed water. The physically adsorbed water at these pressures begins to desorb at pressures below 1 mm Hg. As pressures and temperatures at the sliding interface rise, the desorption of this water is promoted, and friction begins to increase.

One question that may be posed at this particular point is why the friction coefficient was higher at an ambient pressure of 760 than at 10 mm Hg if moisture or water were present under both conditions. The answer to this question may lie in the fact that, at 760 mm Hg, oxygen and nitrogen are physically adsorbed on the carbon surface as well as the physically and chemically adsorbed water. Examination of Fig. 8 indicates that, with a nitrogen bleed containing traces of moisture, the friction coefficient of carbon sliding on 440-C did not increase from 10 to 760 mm Hg; whereas, with the oxygen bleed containing moisture, the friction coefficient did rise in this pressure region. The results indicated oxygen is responsible for the change in friction observed with pressure. Nitrogen can be eliminated because of the small quantities adsorbed and its relatively inert nature. Since oxygen is very readily adsorbed on carbon, a competitive type of reaction for active carbon sites between water and oxygen may have occurred with the result that more oxygen was adsorbed on the carbon than water; thus, the effectiveness of the adsorbed water film was decreased.

The friction coefficients obtained in experiments in which pressure was decreased from atmospheric to the vacuum range were generally lower than those obtained in experiments in which pressure was increased from the vacuum range to atmospheric. A friction experiment was, therefore, conducted with a high-density carbon (reduced adsorption surface) to determine whether the effect could be related to adsorption. The friction results obtained with a high-density carbon sliding on 440-C stainless steel can be seen in Fig. 9a. These data are notable in that the friction remained low at minimum pressures (10^{-8} mm Hg). A curve similar to that obtained previously resulted in a delay in friction increase caused by decreasing pressure. Another possible explanation to consider is the fact that the metal surface that contacted

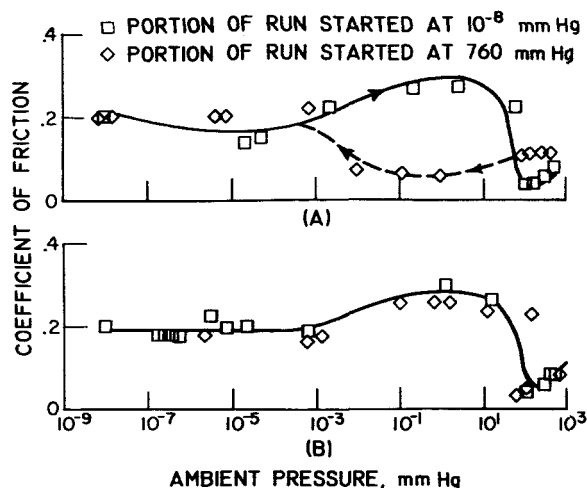


FIG. 9. Effect of ambient pressure on coefficient of friction of high-density carbon sliding on high-density carbon and 440-C stainless steel. Sliding velocity, 390 feet per minute; load, 1000 gm; temperature, 75 F. (a) Carbon on 440-C stainless steel; (b) Carbon on carbon.

the carbon had the predominant influence. Consequently, another experiment was conducted with the high-density carbon sliding on itself; the results obtained are presented in Fig. 9b. The friction data points for both cycles retraced a single curve very closely, and no hysteresis effect in friction coefficient was observed in the experiments started at 760 mm Hg. The results obtained with the metals and the ceramic (aluminum oxide) do indicate hysteresis (Fig. 7). The results may, then, be associated with the mating surfaces. Carbons are not unique in the adsorption of water vapor since metals also will readily adsorb water both physically and chemically (20). Water vapor of the order of 20 monolayers may be physically adsorbed to metal surfaces at 77 F. The water is not only adsorbed on the surface but also within oxide pores and crystal structure (20). At pressures less than 1 mm Hg, not more than one or two monolayers remain physically adsorbed. Just as in carbon, however, chemisorption of water occurs, but, unlike carbons, metals chemisorb the water irreversibly. This chemisorption of water on the metal oxides results in a dissociation of water into hydrogen and hydroxyl groups, which are adsorbed on the oxide surface (20). These films may remain adsorbed to the metal at pressures below 1 mm Hg and may account for friction remaining low to lower ambient pressures.

INFLUENCE OF METAL OXIDES ON THE FRICTION OF CARBON

In Figs. 3-9, the friction coefficients do not exceed 0.38 at ambient pressures to 10^{-9} mm Hg. Work with graphite reported in the literature (1-3) indicated friction coefficients for graphite and carbons in vacuum in excess of 0.5. It is believed that the residual oxides present on metal surfaces aid in preventing such high friction coefficients from being achieved. To test this hypothesis,

an experiment was made with an unimpregnated carbon sliding on electrolytic silver. The results obtained in this experiment are presented in Fig. 10a. At ambient pressures less than 10^{-3} mm Hg, the friction coefficient reached a value of 0.5; it is interesting to note that at

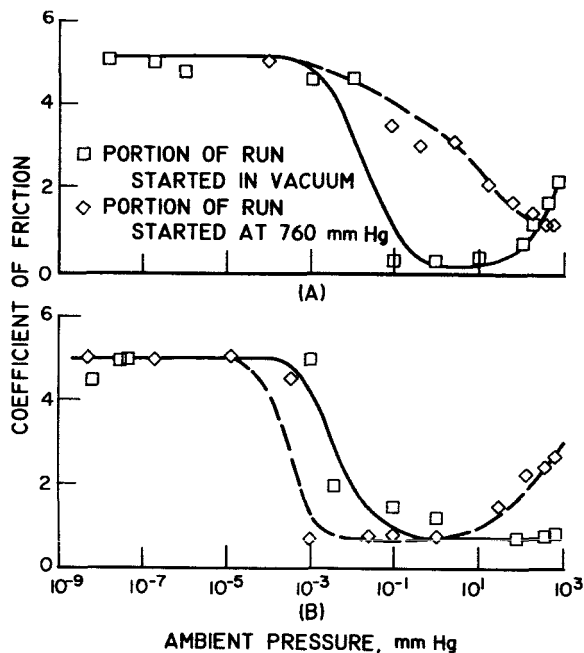


FIG. 10. Effect of ambient pressure on coefficient of friction for impregnated and unimpregnated 20% graphite carbon sliding on electrolytic silver at various ambient pressures. Sliding velocity, 390 feet per minute; load, 1000 gm; temperature, 75 F. (a) Unimpregnated rider; (b) rider impregnated with barium fluoride.

room temperature and at pressures below 10^{-2} mm Hg, the oxides of silver are unstable (24) and will not form. Any existing oxide will readily dissociate and thereby liberate oxygen and leave nascent silver. With the absence of metal surface oxides, friction coefficients of 0.5 were observed with carbons. During sliding, addition of frictional heating resulted in decomposition of the oxide at pressures even higher than 10^{-2} mm Hg; this probably explains the fact that the friction coefficients were considerably higher in experiments started at atmospheric pressure than in experiments started at 10^{-9} mm Hg. Particles of silver were found on the carbon wear surface after the experiment was completed. Silver forms no stable carbides; therefore, the bond between the silver and the carbon must have been a physical one.

The addition of adjuncts to carbons to improve their wear characteristics has long been known. The same carbon material used in Fig. 10a was impregnated with a barium fluoride adjunct and was then run against electrolytic silver; the friction results obtained in this experiment at various pressures are presented in Fig. 10b. Although the coefficient of friction remained low (0.075 to a pressure of 10^{-2} mm Hg), a friction coefficient of 0.5 was obtained from 10^{-3} to 10^{-9} mm Hg,

the same value as obtained with the base grade carbon without the benefit of adjunct. These results indicate that at ambient pressures of outer space in the absence of residual metal surface oxides, adjuncts such as barium fluoride added to carbons will not prevent high friction from occurring. While the adjunct was not effective at 10^{-8} mm Hg, it was effective over the pressure range from 10^{-2} to 10^{-3} mm Hg.

FRICION AND WEAR OF ORGANIC IMPREGNATED CARBONS

A number of carbon compositions containing organics such as phenolic and epoxy additives have been suggested as having possible merit in vacuum. Since organics are, in general, considered to have higher evaporation rates than desirable, evaporation rates of some phenolic and epoxy agents used in carbons were measured; the results obtained are presented in Fig. 11. The evaporation rates for the materials were similar to those of materials known to be useful. Some friction and wear experiments were, therefore, conducted at 10^{-7} mm Hg with carbon specimens that had been impregnated with these various agents. The results obtained in these experiments are presented in Fig. 12a. Data for an unimpregnated carbon are given for reference purposes. The best friction and

wear results in vacuum were obtained with a carbon that had been impregnated with an uncured epoxy.

PTFE has been given consideration by carbon manufacturers because of its lubricating properties; attempts to impregnate carbon with PTFE under varying conditions have been tried with varying degrees of success. A carbon material impregnated with PTFE by three different processes was examined in vacuum to determine the effect of PTFE on the friction characteristics of carbon. In general, the PTFE did not improve the friction and wear characteristics of the carbon in vacuum. This result does not necessarily mean that PTFE would not improve the friction and wear characteristics of carbons. Impregnating carbon with PTFE is quite difficult and, to date, the depth of PTFE penetration into carbon bodies has generally been limited. It is probable, then, that an inadequate amount of PTFE was available at the carbon-metal interface during the sliding process of these experiments. Additional research in this area is warranted.

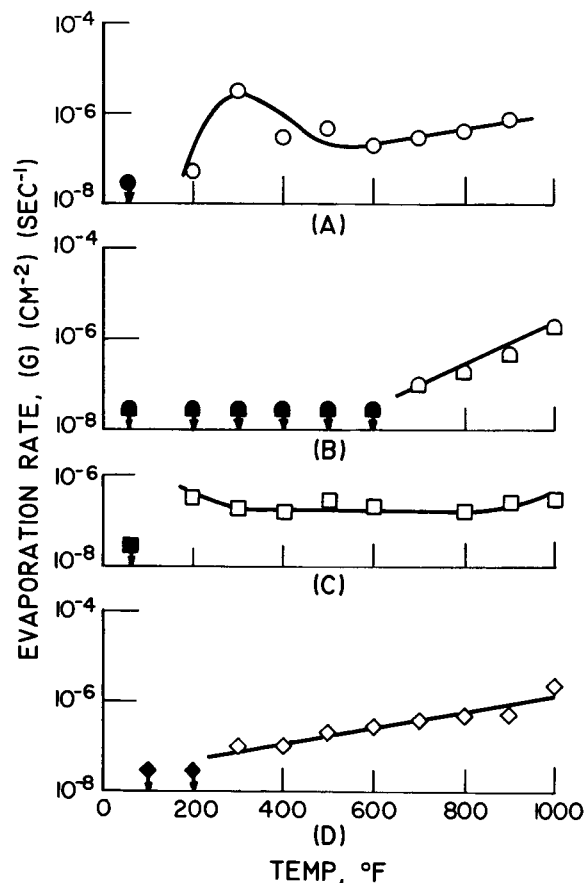


FIG. 11. Evaporation rates for carbon additives. Ambient pressure, 10^{-6} mm Hg. (a) Epoxy resin, (b) cured epoxy resin, (c) epoxy and phenolic resins, (d) phenolic resin.

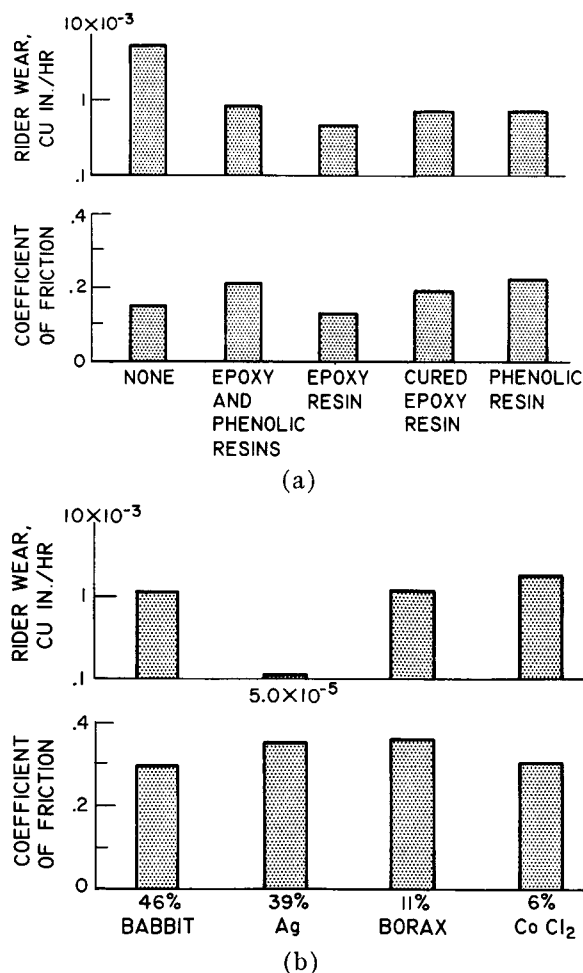


FIG. 12. Friction and wear of carbon materials sliding on 440-C stainless steel in vacuum (10^{-7} mm Hg). Sliding velocity, 390 feet per minute; load, 1000 gm; temperature, 75 F; duration of run, 1 hour. (a) Organic additives, (b) metallic and inorganic additives.

FRICTION AND WEAR OF INORGANIC IMPREGNATED CARBONS

Some friction and wear experiments were also conducted at 10^{-7} mm Hg with various metallic and inorganic impregnants. The metal impregnants were considered to have potential value in "melt" lubrication at the sliding interface while borax could serve as a source of interface moisture for adsorption. The results of these experiments are presented in Fig. 12b. All the base grade carbons were the same with the exception of the cobalt chloride impregnated specimen, which was comparable. The lowest wear obtained with these materials was with the silver impregnated carbon. The low wear may result from a molten silver film at the sliding interface. Examination of the wear area on the carbon rider specimen after the experiment revealed a considerable quantity of silver on the surface. Similar results were obtained in the investigation of Reference 28 with silver impregnated carbons. Density measurements of the carbon bodies revealed a flowing out of silver from the carbon body.

Some approaches that might be taken to improve carbons in vacuum are: (1) the use of high-density carbons, with a selective chemisorption of gases, which improve their performance in vacuum; and (2) the addition of various soft, low melting point metals to porous carbon structures to produce thin film lubrication in vacuum at the interface between carbon and the mating material.

Summary of results

The experimental results obtained in this investigation of the mechanism of lubrication of various carbon materials in vacuum can be summarized as follows:

1. The presence of adsorbed gases on and within the structure of mechanical carbons played an important role in the friction and wear observed for these materials at 10^{-9} mm Hg as well as at atmospheric pressures.

2. The friction coefficient of the high-density carbon materials was not as sensitive to changes in ambient pressure as that of the more porous carbons. The desorption of gases and adsorbed surface films was not as readily achieved with dense carbon bodies as with those of a more porous nature.

3. The presence of residual oxides on metal surfaces against which carbons were run permitted a film of carbon to form on the metal surface. The transfer of carbon is believed to have been achieved by means of a chemisorption of carbon to the oxygen of the metal oxide. The wear in carbon was less when it was run against metals that formed the transferred carbon film than when it was run against metals (e.g., silver and gold) that did not form the transferred carbon films at pressures less than 10^{-3} mm Hg.

4. High coefficients of friction (0.5) were obtained in vacuum (less than 10^{-3} mm Hg) when carbons were run against mating surfaces, such as silver, that did not have oxides on their surfaces. The mechanism responsible

for these friction coefficients may have been related to the physical transfer of large quantities of silver to the carbon surface, that is, silver slid on silver rather than carbon on carbon when carbon films were present on metal oxides.

5. The small quantities of water vapor present in the atmosphere (less than 10^{-4} mg per liter of gas) that are readily adsorbed by carbon influenced both friction and wear. The minimum friction and wear were observed with water vapor present at ambient pressures of 1–10 mm Hg for carbons sliding on various materials.

6. The minimum friction and wear for carbons containing various percentages of graphite in vacuum were achieved with carbons including approximately 20% graphite.

7. With a metal surface (silver) that did not have a residual surface oxide in vacuum, the presence of an adjunct (barium fluoride) in the carbon did not improve its friction characteristics or film transfer properties at 10^{-8} mm Hg. It was effective over the pressure range from 10^{-2} to 10^{-3} mm Hg.

8. Impregnation of carbon bodies with PTFE did not appreciably improve their friction coefficient and wear in vacuum. This may have resulted from the difficulty in effectively impregnating carbon bodies with PTFE, and additional research in this area is warranted.

9. The results of this investigation indicated that further research on the use of carbons in vacuum is warranted.

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